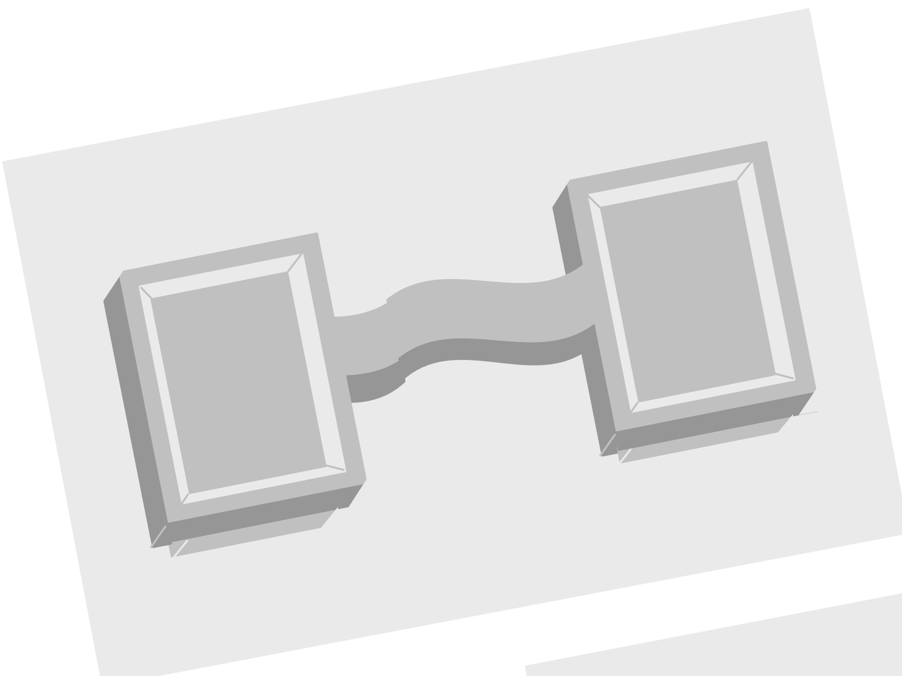
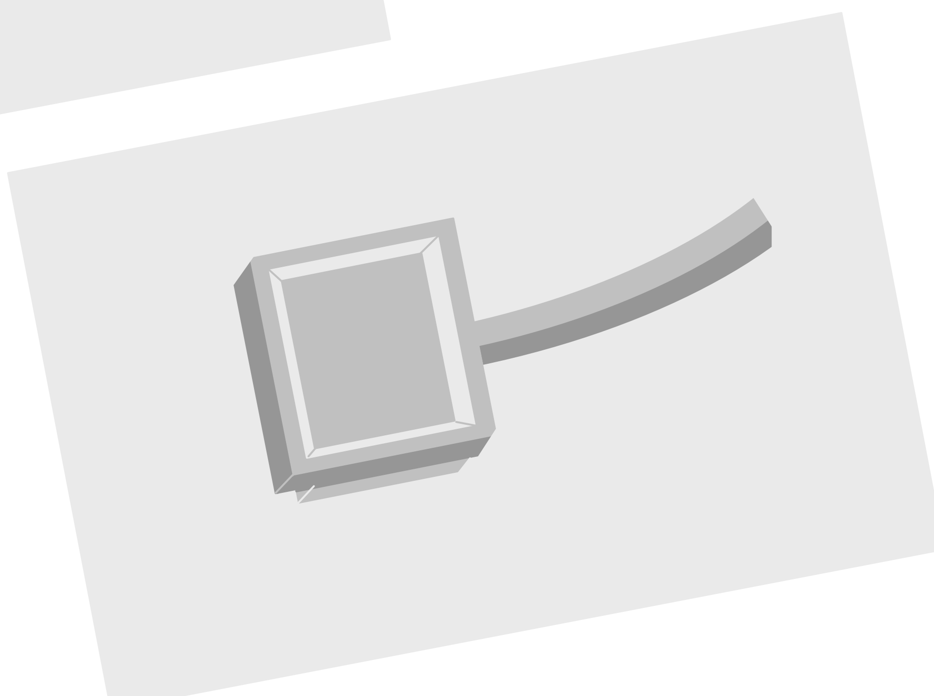
User's Guide for the MEMS Length and Strain Round Robin Experiment Using Optical Interferometry





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USER'S GUIDE FOR THE MEMS LENGTH AND STRAIN ROUND ROBIN EXPERIMENT USING OPTICAL INTERFEROMETRY

ABSTRACT

This is the User's Guide for the MicroElectroMechanical Systems (MEMS) Length and Strain Round Robin Experiment. It provides details concerning the test equipment, the Round Robin Test Chips, the round robin measurements to take on these chips, and the results to report. The round robin measurements include in-plane length, residual strain, and strain gradient measurements using the procedures in three American Society for Testing and Materials (ASTM) standard test methods. An optical interferometer is used to take the measurements. The purpose of the MEMS Length and Strain Round Robin Experiment is to educate the round robin participants concerning these test methods and to provide round robin results for the test methods.

Key words: ASTM, cantilevers, fixed-fixed beams, interferometry, length measurements, MEMS, residual strain, round robin, strain gradient, test structures

USER'S GUIDE FOR THE MEMS LENGTH AND STRAIN ROUND ROBIN EXPERIMENT USING OPTICAL INTERFEROMETRY

1. INTRODUCTION

For the MicroElectroMechanical Systems (MEMS)[1] Length and Strain Round Robin Experiment, an optical interferometer is used to take measurements. Three American Society for Testing and Materials (ASTM) standard test methods have been written for use with this instrument. The first one is for in-plane length measurements, the second one is for residual strain measurements, and the third one is for strain gradient measurements. Standard test methods have a section entitled "Precision and Bias" that reports round robin results using the test method. This section must be included in each test method. The purpose of the MEMS Length and Strain Round Robin Experiment is to educate the round robin participants and to provide round robin results for these Precision and Bias Statements.

Section 2 provides details concerning the MEMS Length and Strain Round Robin Experiment (e.g., details associated with the optical interferometer, the Round Robin Test Chips, the material available for the experiment, and the electronic submission of the data). Sections 3 through 6 provide details concerning the measurements taken in each test chip quadrant. Reproductions of the Web-based data analysis sheets used for submitting the round robin data can be seen in the Appendices.

2. MEMS LENGTH AND STRAIN ROUND ROBIN EXPERIMENT

This section provides details concerning the MEMS Length and Strain Round Robin Experiment. It is divided into four parts. Section 2.1 provides specifications for the optical interferometer, Section 2.2 describes the Round Robin Test Chips, Section 2.3 describes the material available for the experiment, and Section 2.4 discusses the electronic submission of the round robin data.

2.1 *Interferometer Specifications*

For the MEMS Length and Strain Round Robin Experiment, the non-contact optical interferometer[2] must be capable of obtaining a topographical 3-D data set and have software that can export a 2-D data trace. Figure 1 is a sketch of a suitable interferometer. However, any non-contact optical interferometer that has pixel-to-pixel spacings as specified in Table 1 and that is capable of performing the test procedure with a vertical resolution less than 1 nm is permitted. Obtaining this resolution may be done by averaging multiple measurements. The interferometer must be capable of measuring step heights from 0.1 nm to at least 10 μm higher than the step height to be measured.

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[1] MEMS are also referred to as microsystems technology (MST) and micromachines.

[2] In this guide, commercial equipment or instruments may be identified. This does not imply recommendation or endorsement by the National Institute of Standards and Technology (NIST), nor does it imply that the equipment or instruments are the best available for the purpose.

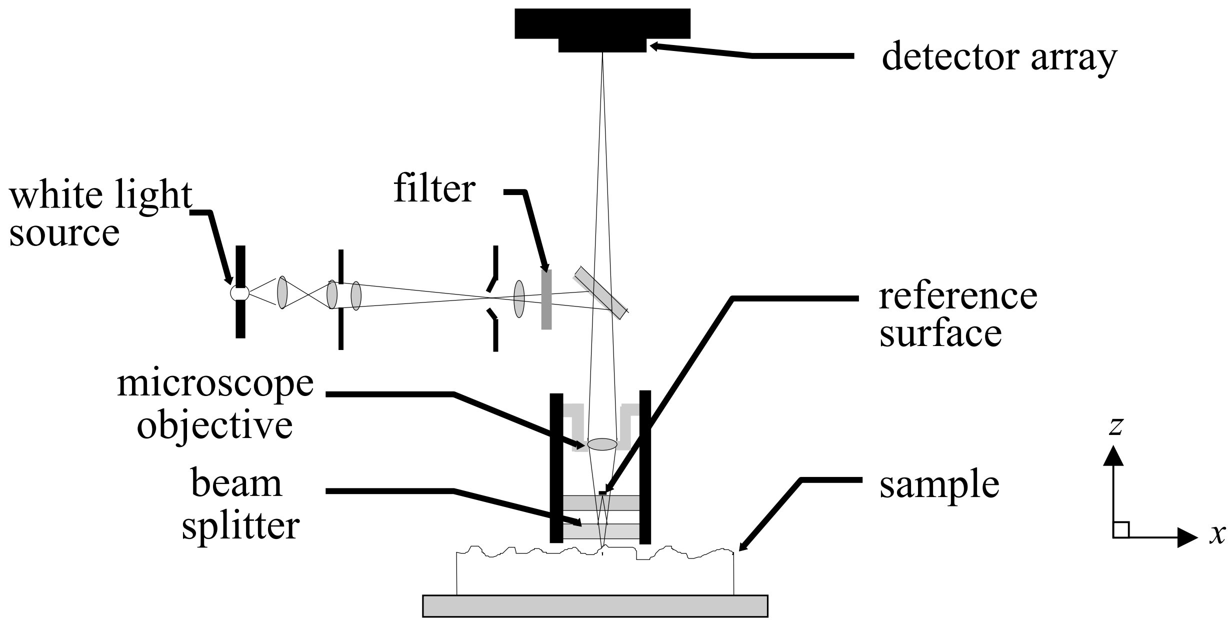

Figure 1. Sketch of optical interferometer.

Table 1 – Interferometer Pixel-to-Pixel Spacing Requirements

Magnification, ×	**Pixel-to-pixel spacing, μm**
5	< 1.57
10	< 0.83
20	< 0.39
40	< 0.21
80	< 0.11

2.2 *Round Robin Test Chips*

Three are two MEMS Round Robin Test Chips – one fabricated on the Multi-User MEMS Processes (MUMPs) and one fabricated on the Multi-User Silicon Carbide (MUSiC) process. The designs for these test chips are depicted in figures 2 and 3, respectively. As can be seen in these figures, the fabrication process designation is specified in the upper right hand corner. (However, the same test chip design in figure 3 was fabricated on both the first and second MUSiC processing runs, therefore the MUSiC-1 fabrication process designation is specified in the upper right hand corner in this figure even though it was fabricated on the second MUSiC processing run.) Participants can obtain the design file (in GDS-II format) for each of the round robin test chips from the Semiconductor Electronics Division (SED) MEMS Length and Strain Round Robin Experiment Web site accessible through the MEMS Project Web Page at http://www.eeel.nist.gov/812/44.htm.

<u>At this time, only a MUMPs test chip will be used in the MEMS Length and Strain Round Robin Experiment</u>. The MUSiC test chips provide more challenging data sets due to the more transparent nature of the key layers. As such, these data sets are not meant for the novice round robin participant. However, this challenging aspect of the data sets may be attractive to equipment manufacturers who are 'pushing the envelope,' so to speak.

For the MUMPs, there are three mechanical layers (Poly1, Poly2, and a double thickness of Poly1 and Poly2). As shown in figure 2, the mechanical layer used as the suspended portion of the test structure is specified with a 'P1' (for Poly1), a 'P2' (for Poly2), or a 'P12' (for a double thickness of Poly1 and Poly2).

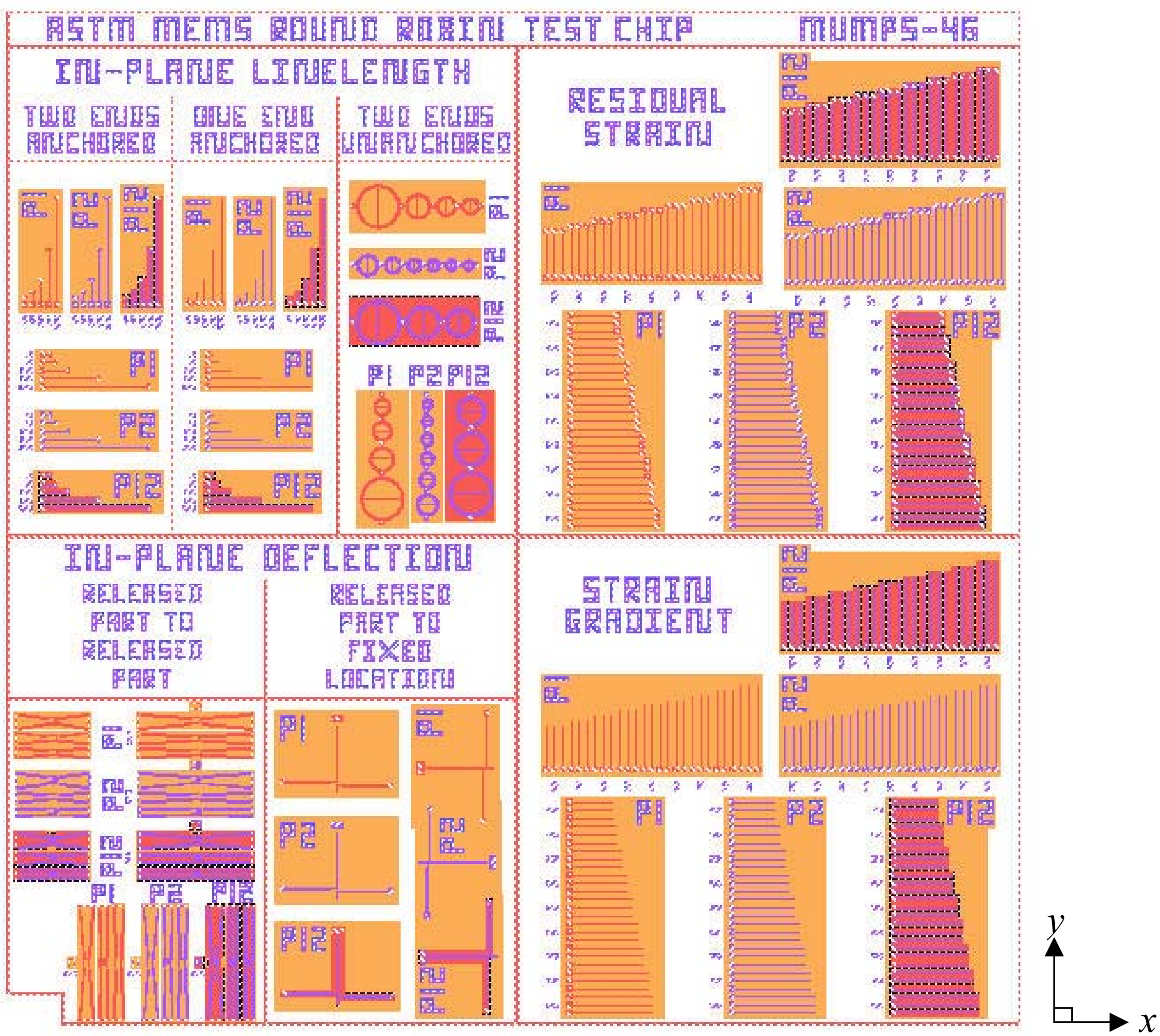

Figure 2. The round robin test chip fabricated on the MUMPs46.

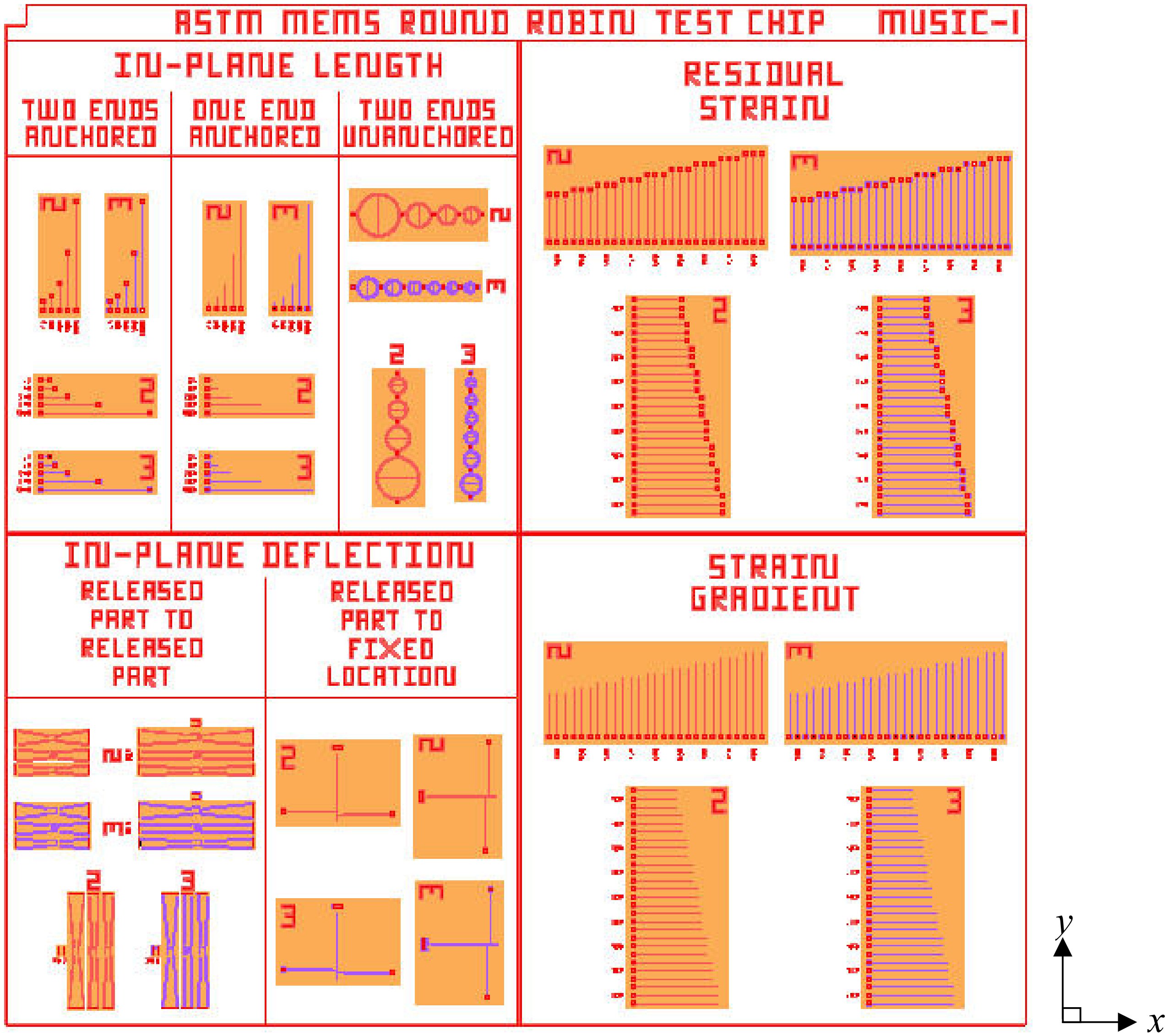

Figure 3. The round robin test chip fabricated on the second MUSiC processing run.

For the MUSiC process, one of two mechanical layers (SiC-2 or SiC-3) is used as the suspended portion of the test structures. As shown in figure 3, the mechanical layer used is specified with a '2' (for SiC-2) or a '3' (for SiC-3) in the design.

Both test chips are divided into the same four quadrants. In quadrant '1' (or Q1, as shown in fig. 4) in-plane linelength measurements are made, in quadrant '2' (or Q2) in-plane deflection measurements are made, in Q3 residual strain measurements are made, and in Q4 strain gradient measurements are made. Measurement-specific test structures for each of the mechanical layers are included in each quadrant. These test structures are given in Table 2 for the test chips shown in figures 2 and 3.

In each quadrant, test structures are provided with both an *x*- and *y*-orientation. For all measurements, orient the test chip with respect to the interferometer such that the best resolution measurement is made. Typically, the interferometer's pixel-to-pixel spacing in the *x*-direction is smaller than the pixel-to-pixel spacing in the *y*-direction, such that better resolution measurements can be made in the *x*-direction. Therefore, if measurements are to be taken on the test structures whose mechanical layer designation is not rotated 90 degrees, then the test chip will appear oriented on the interferometric screen as shown in figures 2 and 3. Conversely, if measurements are to be taken on test structures whose mechanical layer designation is rotated 90 degrees, then the test chip should also be rotated 90 degrees under the interferometric optics.

Q1 in-plane linelength	Q3 residual strain
Q2 in-plane deflection	Q4 strain gradient

Figure 4. The quadrants for the MEMS Round Robin Test Chips in figures 2 and 3.

Table 2 – Quadrant, Measurement, and Associated Test Structures
for the MEMS Round Robin Test Chips in Figures 2 and 3

Quadrant	**Measurement**	**Associated Test Structures**
Q1	In-plane linelength	Two ends anchored: Fixed-fixed beams One end anchored: Cantilevers Two ends unanchored: Rings
Q2	In-plane deflection	Released part to released part: Bow-ties Released part to fixed location: Pointers
Q3	Residual strain	Fixed-fixed beams
Q4	Strain gradient	Cantilevers

2.3 *Material Available for the Experiment*

Three ASTM standard test methods have been written for use with an optical interferometer. They are:

1. E 2244, Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer,
2. E 2245, Test Method for Residual Strain Measurements of Thin, Reflecting Films Using an Optical Interferometer, and
3. E 2246, Test Method for Strain Gradient Measurements of Thin, Reflecting Films Using an Optical Interferometer

and are available both electronically (www.astm.org) and in print (in the *Annual Book of ASTM Standards*, Vol. 03.01, 2003).

Use the appropriate test method to guide you through the measurements.[3] The test method for in-plane length measurements is used for the Q1 and Q2 measurements. The test method for residual strain measurements is used for the Q3 measurements and the test method for strain gradient measurements is used for the Q4 measurements.

If the user has difficulties understanding the technical underpinnings behind the steps in the standard test methods, he or she can consult the NIST Internal Report (NISTIR 6779) that is accessible via the MEMS Length and Strain Round Robin Experiment Web site specified in Section 2.2.

2.4 *Electronic Submission of the Data*

Sections 3 through 6 of this guide provide the participant with details concerning the measurements taken in each test chip quadrant. After the raw, uncalibrated measurements are recorded in the appropriate data analysis sheet, the calculations are performed on-line by pressing the "Calculate and Verify" button. The participant is advised to correct any warnings given at the bottom of the data analysis sheet, afterwhich this form can be submitted to the Round Robin by pushing the "Submit this form to Round Robin" button. Reproductions of the Web-based data analysis sheets can be seen in the Appendices.

For the MEMS Length and Strain Round Robin Experiment, the following number of completed data analysis sheets are requested:

1. Data Analysis Sheet A – 5 MUMPs and 0 MUSiC sheets – (see Section 3.1)
2. Data Analysis Sheet B – 5 MUMPs and 0 MUSiC sheets – (see Section 3.1)
3. Data Analysis Sheet C – 0 MUMPs and 0 MUSiC sheets – (see Section 3.2)
4. Data Analysis Sheet D – 0 MUMPs and 0 MUSiC sheets – (see Section 3.3)
5. Data Analysis Sheet E – 0 MUMPs and 0 MUSiC sheets – (see Section 4.1)
6. Data Analysis Sheet F – 0 MUMPs and 0 MUSiC sheets – (see Section 4.2)
7. Data Analysis Sheet G – 2 MUMPs and 0 MUSiC sheets – (see Section 5)
8. Data Analysis Sheet H – 2 MUMPs and 0 MUSiC sheets – (see Section 6)

Note in the above list that completed data analysis sheets are only requested for Data Analysis Sheets A, B, G, and H. Results from these data analysis sheets will be included in the Precision and Bias Statements. For the particular test structures to be measured, in the round robin, using these data analysis sheets, consult the appropriate section in the above list. Additional measurements may be taken and then analyzed using the other data analysis sheets (i.e., Data Analysis Sheets C, D, E, and F). The data analysis sheets can also be used to verify these measurements. For additional verification, the participant is invited to submit these results to the Round Robin as well.

The completed data analysis sheets will be made available, upon request, to other robin-robin participants.[4] Identifying information concerning whose data it is will be kept confidential. Therefore, it is expected that the round robin participant add no identifiers within their submitted data analysis sheets.

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[3] It is important that the round robin participants use the same procedures. The collected data will be reported in the Precision and Bias Statement towards the end of the standard test method.

[4] If appropriate, the data analysis sheets will also be made available to FiberLead. This was a condition of acceptance to receive round robin test chips fabricated through the MUSiC process.

3. QRADRANT 1: IN-PLANE LINELENGTH MEASUREMENTS

In Q1, the measurements of in-plane linelength, *L*, are made. For in-plane linelength measurements, there are three classes of structures as determined by their end conditions; therefore, Q1 has three subdivisions, as shown in figures 2 and 3. The three classes of structures (or subdivisions) and Q1 test structures are as follows:

1. Two ends anchored (using fixed-fixed beams),
2. One end anchored (using cantilevers), and
3. Two ends unanchored (using rings).

The in-plane linelength measurements on the test structures above are made with an optical interferometer. Many interferometers are purchased with five magnifications. Therefore, for each magnification, a fixed-fixed beam or cantilever is provided in the first and second subdivisions, respectively.[5] Table 3 lists the five magnifications. In the third column, the Q1 design lengths for the fixed-fixed beams and cantilevers are given. In most cases, this length is at least 70 μm less than the calibrated maximum field of view in the *x*-direction,[6] as given in the second column, for a representative interferometer.

Table 3 – The Q1 Design Lengths of Fixed-Fixed Beams and Cantilevers for the Given Interferometric Magnifications

Magnification	**Calibrated Maximum Field of View (in the *x*-direction)**	**Q1 Design Lengths of Fixed-Fixed Beams and Cantilevers**
5×	1165.00 μm	1000 μm
10×	599.998 μm	500 μm
20×	287.00 μm	200 μm
40×	150.000 μm	80 μm
80×	75.0000 μm	25 μm

[5] Due to space limitations, this was not done in the third subdivision using the ring test structures.

[6] For this interferometer, the resolution in the *x*-direction is better than the resolution in the *y*-direction.

3.1 *Two Ends Anchored*

The first class of in-plane linelength structures has two ends anchored. Fixed-fixed beams are designed for these measurements in the first Q1 subdivision, as shown in figures 2, 3, and 5. Five fixed-fixed beams with the design lengths specified in Table 3 are included for each mechanical layer and for each orientation.

In this subdivision, two different data analysis sheets can be used. Measurements from both Data Analysis Sheet A and Data Analysis Sheet B are requested for the MEMS Length and Strain Round Robin Experiment.

Data Analysis Sheet A is for in-plane length measurements when the transitional edges are oriented in different directions. For this data analysis sheet, measurements are requested from Edges "1" and "2," as shown in figures 5 and 6, using Trace "a" or "e." For the MEMS Length and Strain Round Robin Experiment, the participant will be informed in a letter accompanying the MUMPs Round Robin Test Chip as to which orientation of five poly1 fixed-fixed beams to measure. For each of the five assigned poly1 fixed-fixed beams, obtain one 3-D data set with the chip oriented under the interferometric optics as shown in figure 5.[7] Therefore, five 3-D data sets are obtained, each at a different magnification. The design lengths for the five fixed-fixed beams are given in Table 3. Following ASTM test method E2244 for measuring in-plane lengths, record the raw, uncalibrated measurements on Data Analysis Sheet A. This data analysis sheet is accessible via the MEMS Length and Strain Round Robin Experiment Web site specified in Section 2.2. (Data Analysis Sheet A can also be seen in Appendix A.) Press the "Calculate and Verify" button to obtain the results for the fixed-fixed beam. After the data is successfully verified, press the "Submit this form to Round Robin" button to submit these results. Five completed forms using Data Analysis Sheet A are requested. The round robin results from these data analysis sheets will be reported in the Precision and Bias Statement.

Data Analysis Sheet B is for in-plane length measurements when the transitional edges are oriented in the same direction. For this data analysis sheet, measurements are requested from Edges "1" and "5," as shown in figures 5 and 6, using Trace "a" or "e." For the MEMS Length and Strain Round Robin Experiment, the participant will be informed in a letter accompanying the MUMPs Round Robin Test Chip as to which orientation of five poly1 fixed-fixed beams to measure. (They will be the same five fixed-fixed beams as requested above for the measurements for Data Analysis Sheet A. Therefore, the participant may choose whether or not to use the same five 3-D data sets obtained above for Data Analysis Sheet A to also use for Data Analysis Sheet B.) For each of the five assigned poly1 fixed-fixed beams, obtain one 3-D data set with the chip oriented under the interferometric optics as shown in figure 5.[8] Therefore, five 3-D data sets are obtained, each at a different magnification. The design lengths for these measurements are 35 μm longer than the design lengths specified in Table 3 for the given fixed-fixed beam. Following ASTM test method E2244 for measuring in-plane lengths, record the raw, uncalibrated measurements on Data Analysis Sheet B. This data analysis sheet is accessible via the MEMS Length and Strain Round Robin Experiment Web site

[7] This orientation assumes that the interferomter's pixel-to-pixel spacing in the *x*-direction is smaller than the pixel-to-pixel spacing in the *y*-direction.

[8] This orientation assumes that the interferomter's pixel-to-pixel spacing in the *x*-direction is smaller than the pixel-to-pixel spacing in the *y*-direction.

specified in Section 2.2. (Data Analysis Sheet B can also be seen in Appendix B.) Press the "Calculate and Verify" button to obtain the results for the fixed-fixed beam. After the data is successfully verified, press the "Submit this form to Round Robin" button to submit these results. Five completed forms using Data Analysis Sheet B are requested. The round robin results from these data analysis sheets will be reported in the Precision and Bias Statement.

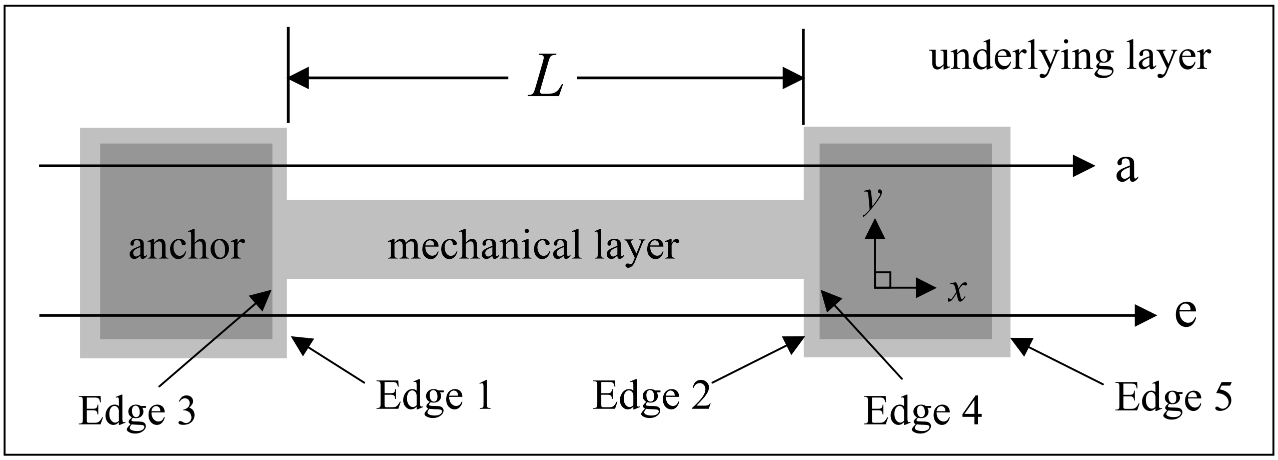

Figure 5. Top view of a fixed-fixed beam test structure.

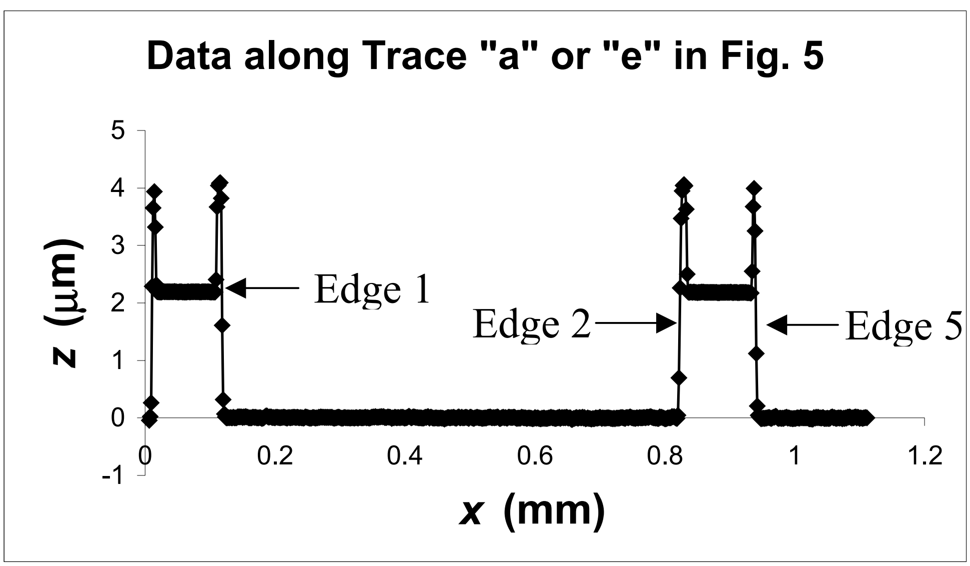

Figure 6. An example of a 2-D data trace taken between the anchors of a fixed-fixed beam test structure.

3.2 *One End Anchored*

The second class of in-plane linelength structures has one end anchored. Cantilevers are designed for these measurements in the second Q1 subdivision, as shown in figures 2, 3, and 7. Five cantilevers with the design lengths specified in Table 3 are included for each mechanical layer and for each orientation.

Measurements from this subdivision are not requested for the MEMS Length and Strain Round Robin Experiment. However, if the participant would like to submit results for additional verification, he or she is invited to do so.

For Data Analysis Sheet C, measurements are requested from Edges "1" and "2," as shown in figures 7, 8, and 9, using Trace "a" or "e" and Trace "b," "c," or "d." Obtain a 3-D data set for a cantilever oriented under the interferometric optics as shown in figure 7.[9] Following ASTM test method E2244 for measuring in-plane lengths, record the raw, uncalibrated measurements on Data Analysis Sheet C. This data analysis sheet is accessible via the MEMS Length and Strain Round Robin Experiment Web site specified in Section 2.2. (Data Analysis Sheet C can also be seen in Appendix C.) Press the "Calculate and Verify" button to obtain the results for the cantilever.

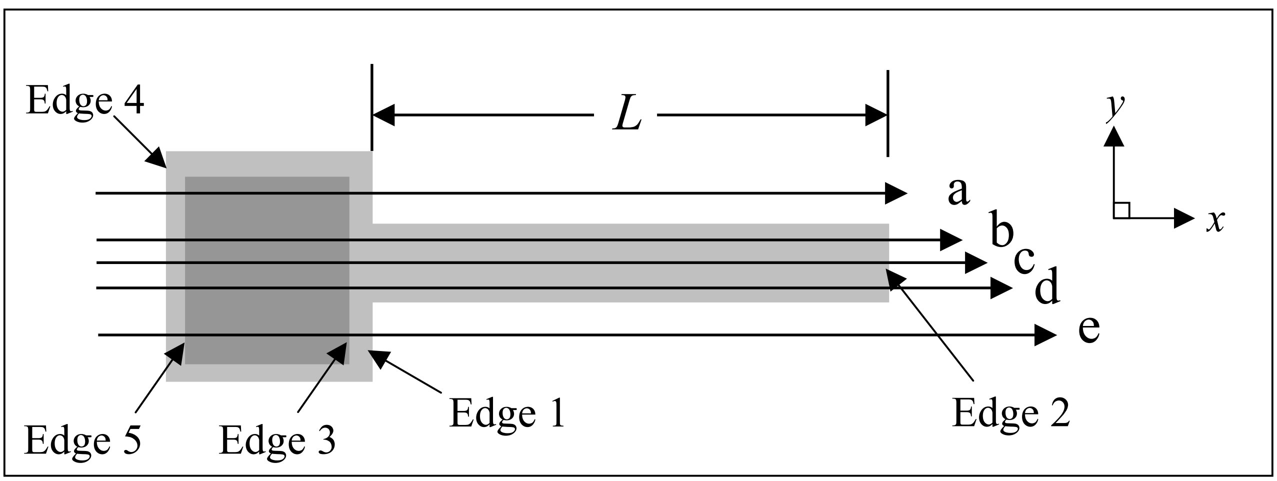

Figure 7. Top view of a cantilever test structure.

[9] This orientation assumes that the interferomter's pixel-to-pixel spacing in the *x*-direction is smaller than the pixel-to-pixel spacing in the *y*-direction.

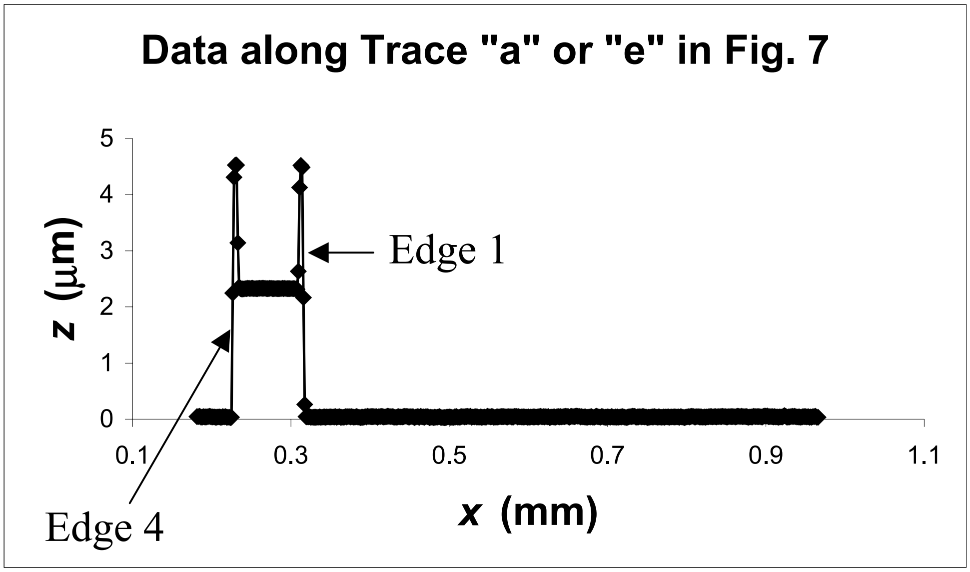

Figure 8. An example of a 2-D data trace adjacent to a cantilever.

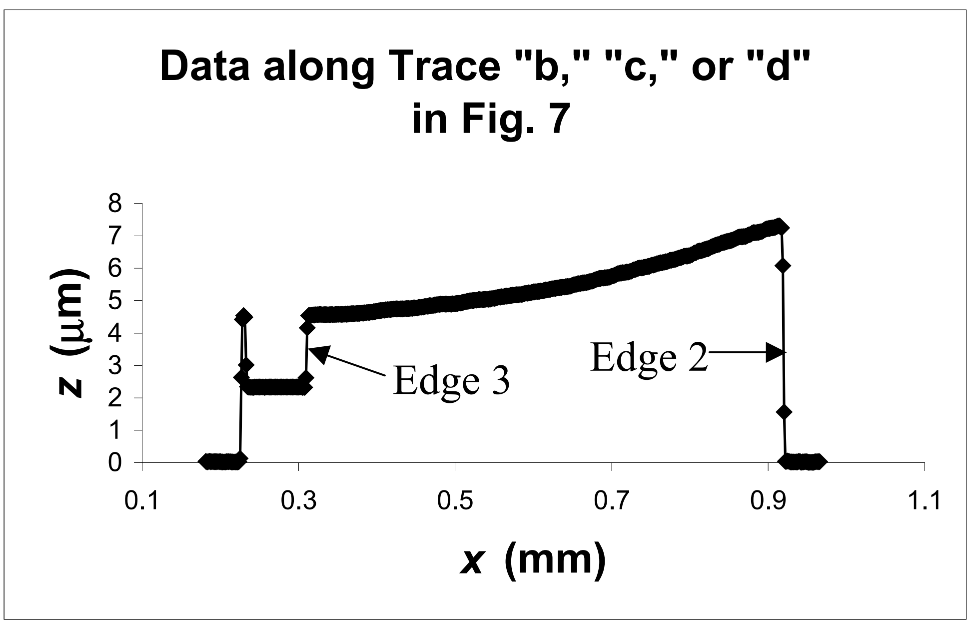

Figure 9. An example of a 2-D data trace along a cantilever.

3.3 *Two Ends Unanchored*

The third class of in-plane linelength structures has two ends unanchored. Rings are designed for these measurements in the third Q1 subdivision, as shown in figures 2, 3, and 10. Three to six rings are included for each mechanical layer and for each orientation.

Measurements from this subdivision are not requested for the MEMS Length and Strain Round Robin Experiment. However, if the participant would like to submit results for additional verification, he or she is invited to do so.

For Data Analysis Sheet D, measurements are requested from Edges "1" and "2," as shown in figure 10, using Trace "a" or "b." Obtain a 3-D data set for a ring oriented under the interferometric optics as shown in figure 10.[10] Use the highest magnification possible to measure this dimension. Following ASTM test method E2244 for measuring in-plane lengths, record the raw, uncalibrated measurements on Data Analysis Sheet D. This data analysis sheet is accessible via the MEMS Length and Strain Round Robin Experiment Web site specified in Section 2.2. (Data Analysis Sheet D can also be seen in Appendix D.) Press the "Calculate and Verify" button to obtain the results for the ring.

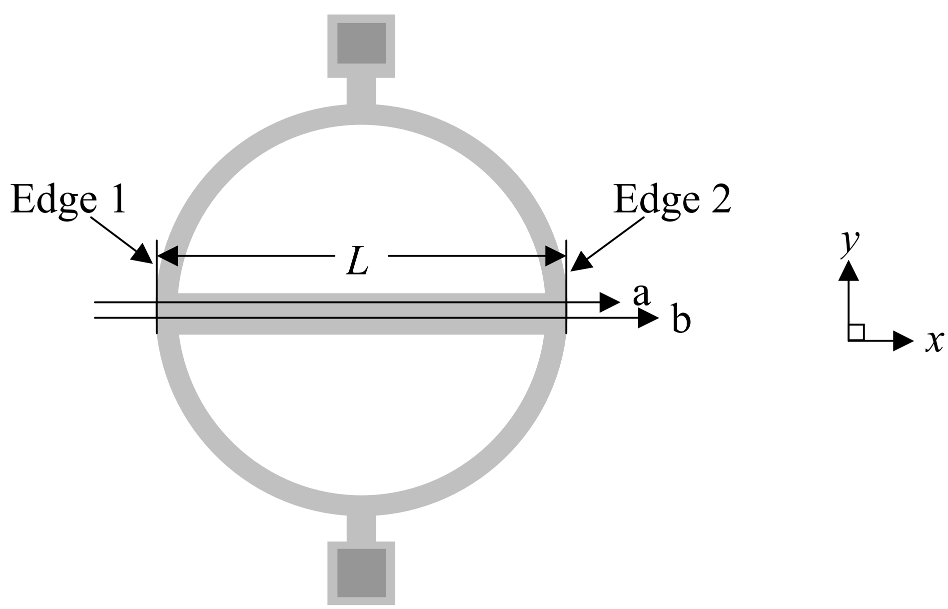

Figure 10. A ring test structure.

[10] This orientation assumes that the interferomter's pixel-to-pixel spacing in the *x*-direction is smaller than the pixel-to-pixel spacing in the *y*-direction.

4. QUADRANT 2: IN-PLANE DEFLECTION MEASUREMENTS

In Q2, the measurements of in-plane deflection, *D*, are made. For in-plane deflection measurements, the in-plane length is taken between two released parts or between a released part and a fixed location. Therefore, Q2 has two subdivisions, as shown in figures 2 and 3. For these two subdivisions, the Q2 test structures are bow-ties and pointers, respectively.

4.1 *Released Part to Released Part*

The first type of in-plane deflection measurement is between two released parts. Bow-tie test structures are designed for these measurements in the first Q2 subdivision, as shown in figures 2, 3, and 11. Bow-ties are included for each mechanical layer and for each orientation.

Measurements from this subdivision are not requested for the MEMS Length and Strain Round Robin Experiment. However, if the participant would like to submit results for additional verification, he or she is invited to do so.

For Data Analysis Sheet E, measurements are requested from Edges "1" and "2," as shown in figure 11, using Trace "a" or "b." Obtain a 3-D data set for a bow-tie test structure oriented under the interferometric optics as shown in figure 11.[11] Use the highest magnification possible for the measurement to be taken. Since the design length between the released parts is 38.5 μm, the magnification should be 80× according to the data in Table 3. Following ASTM test method E2244 for measuring in-plane lengths, record the raw, uncalibrated measurements on Data Analysis Sheet E. This data analysis sheet is accessible via the MEMS Length and Strain Round Robin Experiment Web site specified in Section 2.2. (Data Analysis Sheet E can also be seen in Appendix E.) Press the "Calculate and Verify" button to obtain the results for the bow-tie test structure.

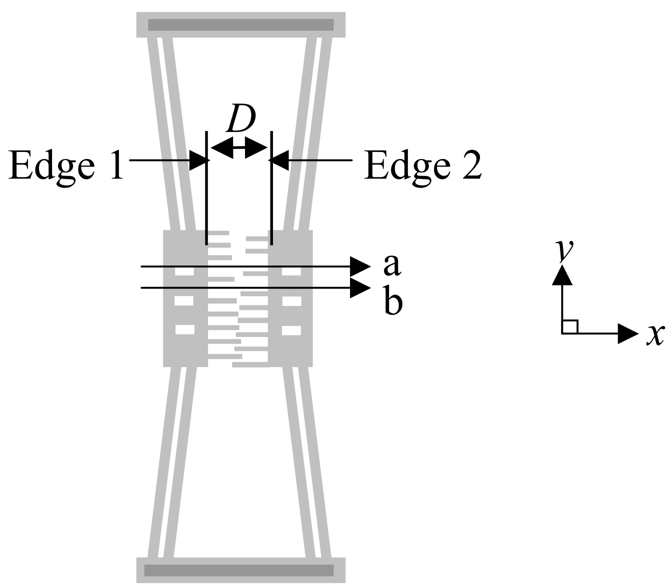

Figure 11. A bow-tie test structure.

[11] This orientation assumes that the interferomter's pixel-to-pixel spacing in the *x*-direction is smaller than the pixel-to-pixel spacing in the *y*-direction.

4.2 *Released Part to Fixed Location*

The second type of in-plane deflection measurement is between a released part and a fixed location. Pointer test structures are designed for these measurements in the second Q2 subdivision, as shown in figures 2, 3, and 12. A pointer is included for each mechanical layer and for each orientation.

Measurements from this subdivision are not requested for the MEMS Length and Strain Round Robin Experiment. However, if the participant would like to submit results for additional verification, he or she is invited to do so.

For Data Analysis Sheet F and the pointer test structure shown in figure 12, measurements are requested from Edges "1" and "2," as shown in figure 13, using Traces "c" and "d." Obtain a 3-D data set for a pointer test structure oriented under the interferometric optics as shown in figure 12.[12] Use the highest magnification possible (i.e., 80×) for the measurement of D_1, as shown in figure 13 between an x-value in Trace "c" and an x-value in Trace "d." Following ASTM test method E2244 for measuring in-plane lengths, record the raw, uncalibrated measurements on Data Analysis Sheet F. This data analysis sheet is accessible via the MEMS Length and Strain Round Robin Experiment Web site specified in Section 2.2. (Data Analysis Sheet F can also be seen in Appendix F.) Press the "Calculate and Verify" button to obtain the results for the pointer test structure.

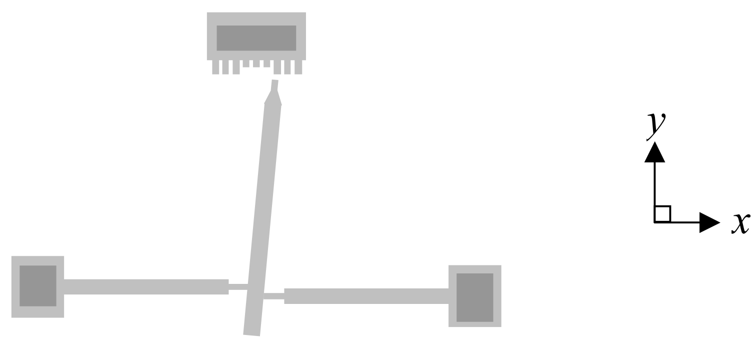

Figure 12. A pointer test structure after the sacrificial layer has been removed.

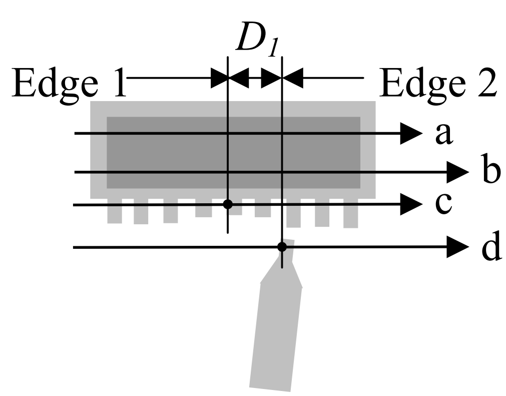

Figure 13. A portion of the pointer test structure shown in figure 12.

[12] This orientation assumes that the interferomter's pixel-to-pixel spacing in the x-direction is smaller than the pixel-to-pixel spacing in the y-direction.

5. QUADRANT 3: RESIDUAL STRAIN MEASUREMENTS

In Q3, residual strain measurements are made. Fixed-fixed beams are provided for this purpose as shown in figures 2, 3, and 14. The fixed-fixed beam design lengths are 400, 450, 500, 550, 600, 650, 700, 750, and 800 μm. There are three fixed-fixed beams designed at each length. Therefore, there are twenty-seven fixed-fixed beams for each mechanical layer and for each orientation.

<u>Measurements from Data Analysis Sheet G are requested for the MEMS Length and Strain Round Robin Experiment. More specifically, measurements from two poly1 fixed-fixed beams on the MUMPs chip are requested. The participant will be informed of the fixed-fixed beams to be measured in a letter accompanying the Round Robin Test Chip.</u>

For Data Analysis Sheet G, measurements are requested from Edges "1" and "2," as shown in figure 14, using Trace "a" or "e." Data points along the fixed-fixed beam, as shown in figure 15, are also requested from Traces "b," "c," and "d." The fixed-fixed beam should be oriented under the interferometric optics as shown in figure 14.[13] For each fixed-fixed beam, obtain a 3-D data set using the highest magnification possible for the measurements. Given the design lengths specified above and the data in Table 3, the magnification should be 10× for those fixed-fixed beams with design lengths of 550 μm and below. The magnification should be 5× for the remainder of the fixed-fixed beams.

Following ASTM test method E2245 for measuring residual strain, record the raw, uncalibrated measurements on Data Analysis Sheet G. This data analysis sheet is accessible via the MEMS Length and Strain Round Robin Experiment Web site specified in Section 2.2. (Data Analysis Sheet G can also be seen in Appendix G.) Press the "Calculate and Verify" button to obtain the results for the fixed-fixed beam. After the data is successfully verified, press the "Submit this form to Round Robin" button to submit these results. Two completed forms using Data Analysis Sheet G are requested. The round robin results from these data analysis sheets will be reported in the Precision and Bias Statement.

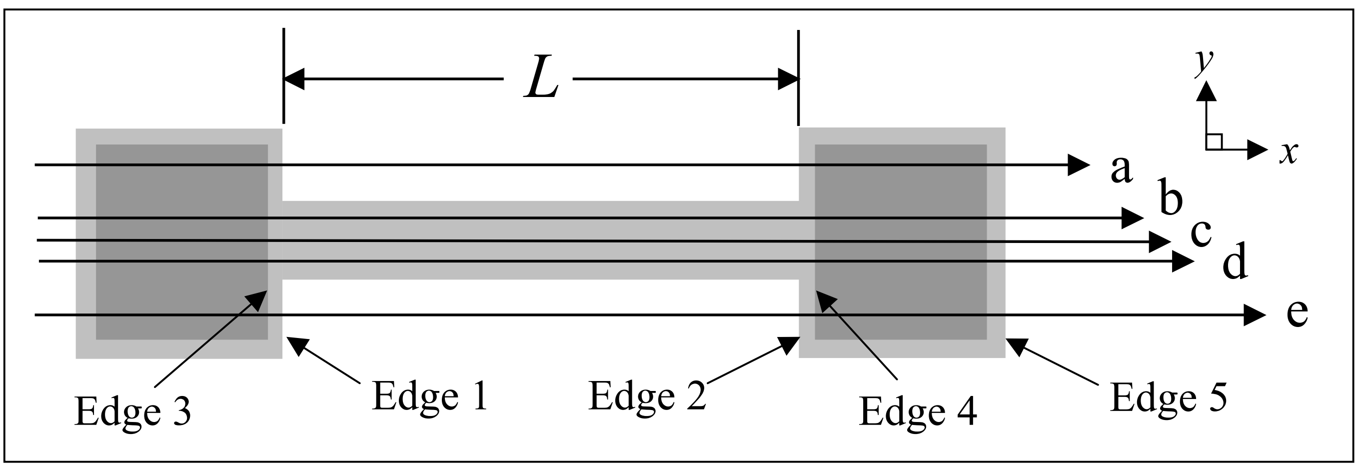

Figure 14. Top view of a fixed-fixed beam test structure.

[13] This orientation assumes that the interferomter's pixel-to-pixel spacing in the *x*-direction is smaller than the pixel-to-pixel spacing in the *y*-direction.

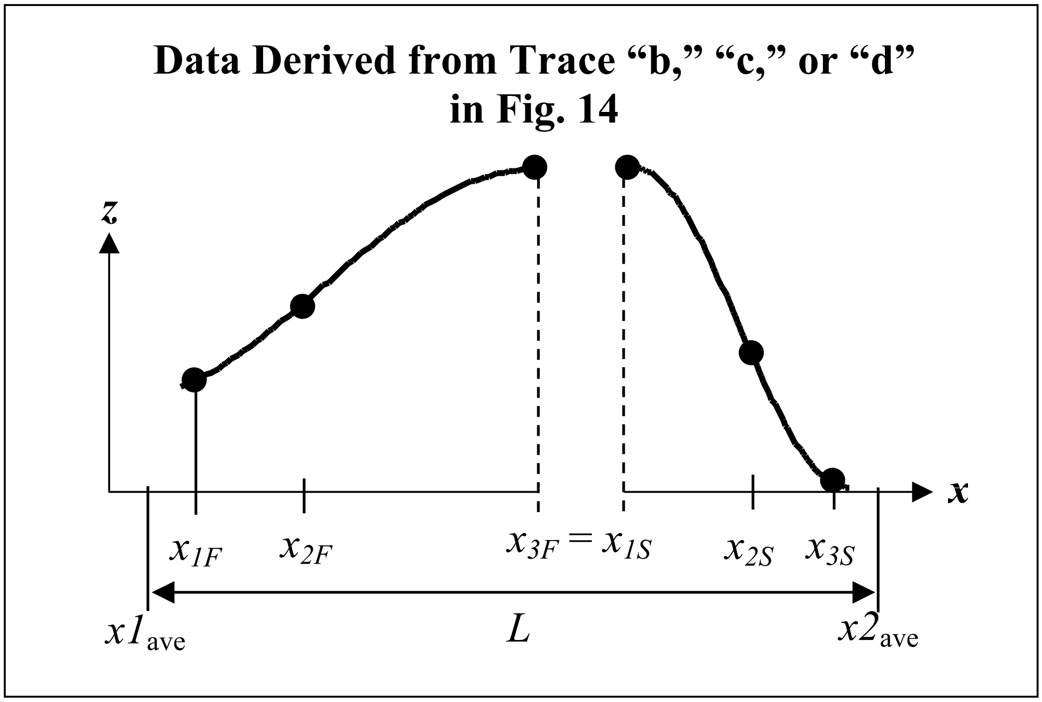

Figure 15. Two data sets derived from an abbreviated data trace along a fixed-fixed beam. The data in the figure above has been exaggerated.

6. QUADRANT 4: STRAIN GRADIENT MEASUREMENTS

In Q4, strain gradient measurements are made. Cantilevers are provided for this purpose as shown in figures 2, 3, and 16. The cantilever design lengths are 400, 450, 500, 550, 600, 650, 700, 750, and 800 μm. There are three cantilevers designed at each length. Therefore, there are twenty-seven cantilevers for each mechanical layer and for each orientation.

For the MEMS Length and Strain Round Robin Experiment, measurements from two poly1 cantilevers on the MUMPs chip are requested using Data Analysis Sheet H. The participant will be informed of the cantilevers to be measured in a letter accompanying the Round Robin Test Chip.

For Data Analysis Sheet H, measurements are requested from Edge "1," as shown in figure 16, using Trace "a" or "e." Data points along the cantilever, as shown in figure 17, are also requested from Traces "b," "c," and "d." The cantilever should be oriented under the interferometric optics as shown in figure 16.[14] For each cantilever, obtain a 3-D data set using the highest magnification possible for the measurements. Given the design lengths specified above and the data in Table 3, the magnification should be 10× for those cantilevers with design lengths of 550 μm and below. The magnification should be 5× for the remainder of the cantilevers.

Following ASTM test method E2246 for strain gradient measurements, record the raw, uncalibrated measurements on Data Analysis Sheet H. This data analysis sheet is accessible via the MEMS Length and Strain Round Robin Experiment Web site specified in Section 2.2. (Data Analysis Sheet H can also be seen in Appendix H.) Press the "Calculate and Verify" button to obtain the results from the cantilever. After the data is successfully verified, press the "Submit this form to Round Robin" button to submit these results. Two completed forms using Data Analysis Sheet H are requested. The round robin results from these data analysis sheets will be reported in the Precision and Bias Statement.

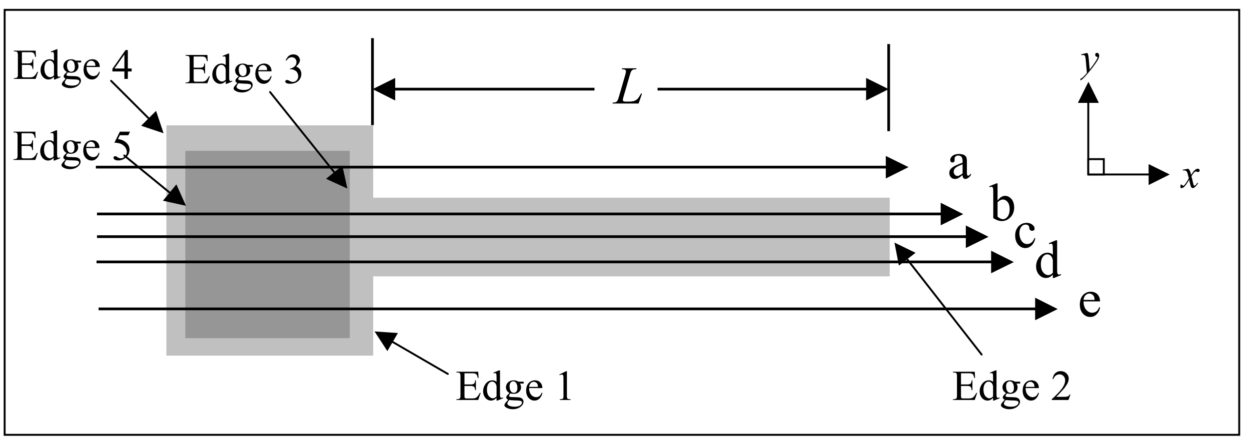

Figure 16. Top view of a cantilever test structure.

[14] This orientation assumes that the interferomter's pixel-to-pixel spacing in the x-direction is smaller than the pixel-to-pixel spacing in the y-direction.

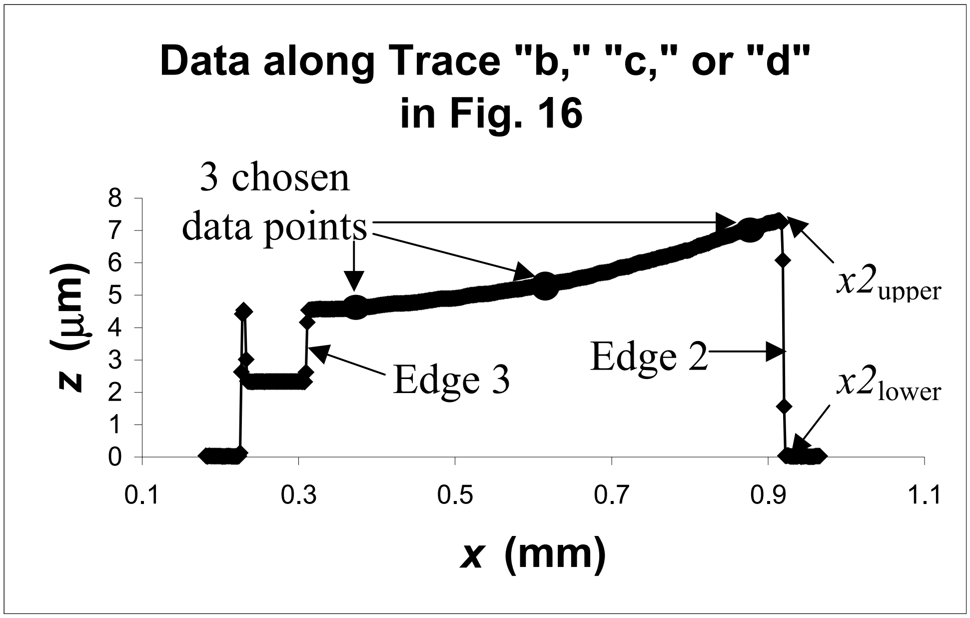

Figure 17. A 2-D data trace used to find three data points.

APPENDIX A – Data Analysis Sheet A

Data analysis sheet for in-plane linelength measurements with two ends anchored

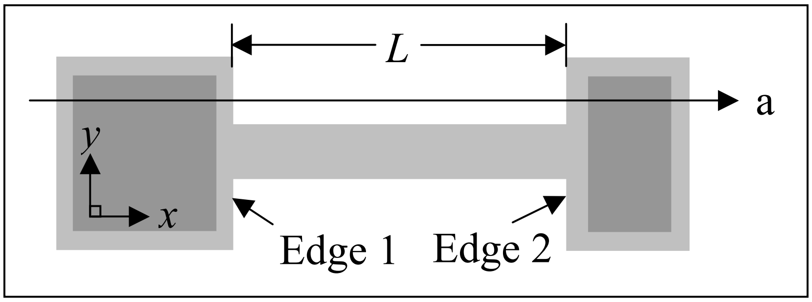

Figure A.1. Top view of a fixed-fixed beam test structure depicting the measurement to be made.

To obtain the following measurements, consult ASTM standard test method E2244 entitled "Standard Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer."

---

filename of 3-D data set (optional) = ☐

filename of 2-D data trace (optional) = ☐

material = Poly1 ● Poly2 ○ stacked Poly1 and Poly2 ○

SiC-2 ○ SiC-3 ○

design length = ☐ µm

magnification = ☐ ×

x-calibration factor (for the given magnification) = $calx$ = ☐

alignment ensured ? Yes ○ No ●

Input Sample Data | Reset this form

INPUTS (uncalibrated values):

$x1_{max}$ (i.e., $x1_{upper}$) = ☐ µm

$x1_{min}$ (i.e., $x1_{lower}$) = ☐ µm ($x1_{min} > x1_{max}$)

$x2_{min}$ (i.e., $x2_{lower}$) = ☐ µm ($x2_{min} > x1_{min}$)

$x2_{max}$ (i.e., $x2_{upper}$) = ☐ µm ($x2_{max} > x2_{min}$)

Calculate and Verify | Clear Outputs

OUTPUTS (calibrated values):

$L_{min} = (x2_{min} - x1_{min}) * calx$ = ☐ µm

$L_{max} = (x2_{max} - x1_{max}) * calx$ = ☐ µm

$L = (L_{min} + L_{max}) / 2$ = ☐ µm

$u_c = (L_{max} - L_{min}) / 6$ = ☐ µm

Make any necessary changes before submitting this form.

1. [ ] Please fill out the entire form.
2. [ ] The design length should be 25, 80, 200, 500, or 1000 μm.
3. [ ] The measured value for *L* is more than 5 μm from the design length.
4. [ ] Is the magnification appropriate given the design length ?
5. [ ] The *x*-calibration factor is "1." Has your data been calibrated ?
6. [ ] Alignment has not been ensured.
7. [ ] $x1_{min}$ should be greater than $x1_{max}$.
8. [ ] $x2_{min}$ should be greater than $x1_{min}$.
9. [ ] $x2_{max}$ should be greater than $x2_{min}$.
10. [ ] The calibrated values for $x1_{min}$ and $x1_{max}$ are greater than 10 μm apart.
11. [ ] The calibrated values for $x2_{min}$ and $x2_{max}$ are greater than 10 μm apart.

Please enter your email address: [ ]

[Submit this form to Round Robin] [Reset this form]
(The 'submit' operation may take a minute.)

Return to Main Round Robin Web Page.

APPENDIX B – Data Analysis Sheet B

Data analysis sheet for in-plane length measurements when the transitional edges defining *L* are oriented in the same direction

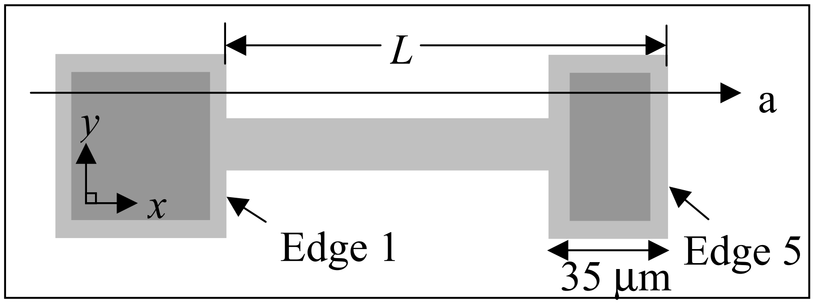

Figure B.1. Top view of a fixed-fixed beam test structure depicting the measurement to be made.

To obtain the following measurements, consult ASTM standard test method E2244 entitled "Standard Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer."

---

filename of 3-D data set (optional) = [ ]
filename of 2-D data trace (optional) = [ ]
material = Poly1 ● Poly2 ○ stacked Poly1 and Poly2 ○
SiC-2 ○ SiC-3 ○
design length = [ ] µm
magnification = [ ] ×
x-calibration factor (for the given magnification) = *calx* = [ ]
alignment ensured ? Yes ○ No ●

Input Sample Data | Reset this form

INPUTS (uncalibrated values):

$x1_{max}$ (i.e., $x1_{upper}$) = [ ] µm
$x1_{min}$ (i.e., $x1_{lower}$) = [ ] µm ($x1_{min} > x1_{max}$)
$x5_{min}$ (i.e., $x5_{upper}$) = [ ] µm ($x5_{min} > x1_{min}$)
$x5_{max}$ (i.e., $x5_{lower}$) = [ ] µm ($x5_{max} > x5_{min}$)

sep (for the given magnification) = [ ] µm
Use 'lower' or 'upper' values for calculation ? Lower ● Upper ○

Calculate and Verify | Clear Outputs

OUTPUTS (calibrated values):

$L_{min} = (x5_{min} - x1_{min}) * calx =$ ____ µm
$L_{max} = (x5_{max} - x1_{max}) * calx =$ ____ µm
$L = (L_{min} + L_{max}) / 2 =$ ____ µm
$u_c = (L_{max} - L_{min}) / 6 =$ ____ µm

L (using lower values) $= (x5_{lower} - x1_{lower}) * calx =$ ____ µm
L (using upper values) $= (x5_{upper} - x1_{upper}) * calx =$ ____ µm
$u_c = (2 * sep * calx) / 3 =$ ____ µm

Make any necessary changes before submitting this form.

1. ☐ Please fill out the entire form.
2. ☐ The design length should be 60, 115, 235, 535, or 1035 µm.
3. ☐ The measured value for L is more than 5 µm from the design length.
4. ☐ Is the magnification appropriate given the design length ?
5. ☐ The x-calibration factor is "1." Has your data been calibrated ?
6. ☐ Alignment has not been ensured.
7. ☐ $x1_{min}$ should be greater than $x1_{max}$.
8. ☐ $x5_{min}$ should be greater than $x1_{min}$.
9. ☐ $x5_{max}$ should be greater than $x5_{min}$.
10. ☐ The calibrated values for $x1_{min}$ and $x1_{max}$ are greater than 10 µm apart.
11. ☐ The calibrated values for $x5_{min}$ and $x5_{max}$ are greater than 10 µm apart.
12. ☐ *sep* is greater than 2 µm or less than or equal to 0 µm. Is this correct ?

Please enter your email address: ____

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APPENDIX C – Data Analysis Sheet C

Data analysis sheet for in-plane linelength measurements with one end anchored

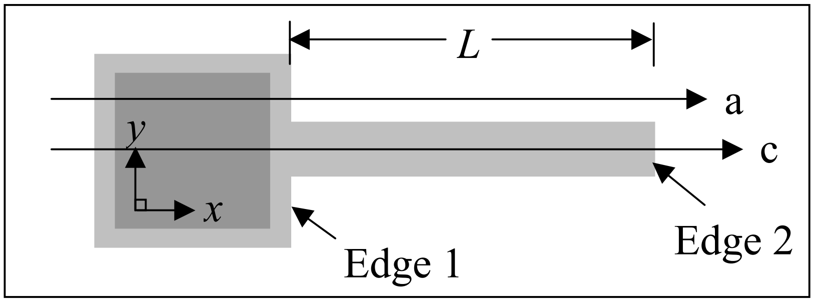

Figure C.1. Top view of a cantilever test structure depicting the measurement to be made.

To obtain the following measurements, consult ASTM standard test method E2244 entitled "Standard Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer."

---

filename of 3-D data set (optional) = [ ]

filename of 2-D data traces (optional) = [ ] [ ]

material = Poly1 ● Poly2 ○ stacked Poly1 and Poly2 ○ SiC-2 ○ SiC-3 ○

design length = [ ] μm

magnification = [ ] ×

x-calibration factor (for the given magnification) = *calx* = [ ]

alignment ensured ? Yes ○ No ●

Input Sample Data | Reset this form

INPUTS (uncalibrated values):

$x1_{max}$ (i.e., $x1_{upper}$) = [ ] μm

$x1_{min}$ (i.e., $x1_{lower}$) = [ ] μm ($x1_{min} > x1_{max}$)

$x2_{min}$ (i.e., $x2_{upper}$) = [ ] μm ($x2_{min} > x1_{min}$)

$x2_{max}$ (i.e., $x2_{lower}$) = [ ] μm ($x2_{max} > x2_{min}$)

Calculate and Verify | Clear Outputs

OUTPUTS (calibrated values):

$L_{min} = (x2_{min} - x1_{min}) * calx =$ ____ µm
$L_{max} = (x2_{max} - x1_{max}) * calx =$ ____ µm
$L = (L_{min} + L_{max}) / 2 =$ ____ µm
$u_c = (L_{max} - L_{min}) / 6 =$ ____ µm

Make any necessary changes before submitting this form.

1. ☐ Please fill out the entire form.
2. ☐ The design length should be 25, 80, 200, 500, or 1000 µm.
3. ☐ The measured value for L is more than 5 µm from the design length.
4. ☐ Is the magnification appropriate given the design length ?
5. ☐ The x-calibration factor is "1." Has your data been calibrated ?
6. ☐ Alignment has not been ensured.
7. ☐ $x1_{min}$ should be greater than $x1_{max}$.
8. ☐ $x2_{min}$ should be greater than $x1_{min}$.
9. ☐ $x2_{max}$ should be greater than $x2_{min}$.
10. ☐ The calibrated values for $x1_{min}$ and $x1_{max}$ are greater than 10 µm apart.
11. ☐ The calibrated values for $x2_{min}$ and $x2_{max}$ are greater than 10 µm apart.

Please enter your email address: ____

Submit this form to Round Robin | Reset this form

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APPENDIX D – Data Analysis Sheet D
Data analysis sheet for in-plane linelength measurements with two ends unanchored

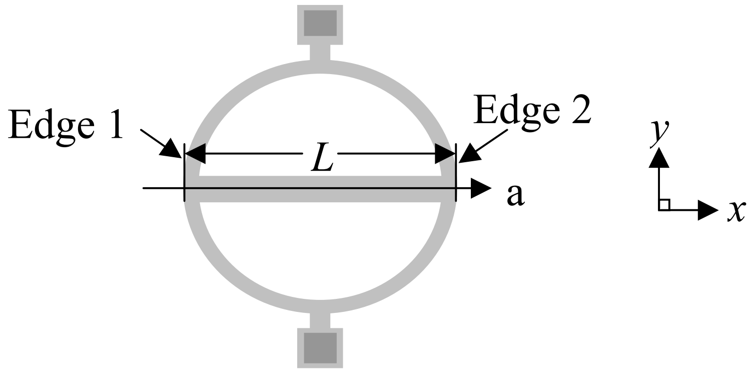

Figure D.1. Top view of ring test structure depicting the measurement to be made.

To obtain the following measurements, consult ASTM standard test method E2244 entitled "Standard Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer."

---

filename of 3-D data set (optional) = [ ]
filename of 2-D data trace (optional) = [ ]
material = Poly1 ● Poly2 ○ stacked Poly1 and Poly2 ○
SiC-2 ○ SiC-3 ○
design length (optional) = [ ] μm
which ring (from left-to-right or top-to-bottom) ?
First ● Second ○ Third ○ Fourth ○ Fifth ○ Sixth ○
magnification = [ ] ×
x-calibration factor (for the given magnification) = *calx* = [ ]
alignment ensured ? Yes ○ No ●

[Input Sample Data] [Reset this form]

INPUTS (uncalibrated values):

$x1_{max}$ (i.e., $x1_{lower}$) = [ ] μm
$x1_{min}$ (i.e., $x1_{upper}$) = [ ] μm ($x1_{min} > x1_{max}$)
$x2_{min}$ (i.e., $x2_{upper}$) = [ ] μm ($x2_{min} > x1_{min}$)
$x2_{max}$ (i.e., $x2_{lower}$) = [ ] μm ($x2_{max} > x2_{min}$)

Calculate and Verify | Clear Outputs

OUTPUTS (calibrated values):

$L_{\min} = (x2_{\min} - x1_{\min}) * calx =$ ____ μm
$L_{\max} = (x2_{\max} - x1_{\max}) * calx =$ ____ μm
$L = (L_{\min} + L_{\max}) / 2 =$ ____ μm
$u_c = (L_{\max} - L_{\min}) / 6 =$ ____ μm

Make any necessary changes before submitting this form.

1. Please fill out the entire form.
2. Is the magnification appropriate for the given measurement ?
3. The *x*-calibration factor is "1." Has your data been calibrated ?
4. Alignment has not been ensured.
5. $x1_{\min}$ should be greater than $x1_{\max}$.
6. $x2_{\min}$ should be greater than $x1_{\min}$.
7. $x2_{\max}$ should be greater than $x2_{\min}$.
8. The calibrated values for $x1_{\min}$ and $x1_{\max}$ are greater than 10 μm apart.
9. The calibrated values for $x2_{\min}$ and $x2_{\max}$ are greater than 10 μm apart.

Please enter your email address: ____

Submit this form to Round Robin | Reset this form

(The 'submit' operation may take a minute.)

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APPENDIX E – Data Analysis Sheet E

Data analysis sheet for in-plane deflection measurements from released part to released part

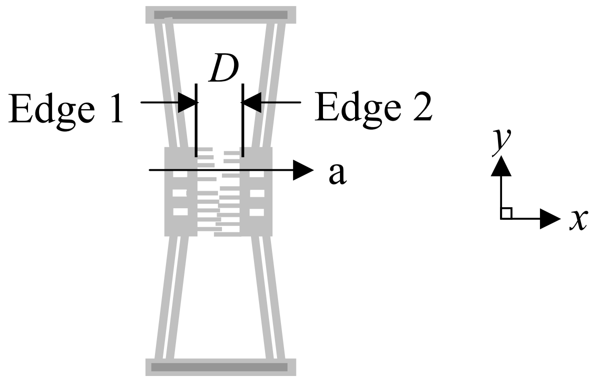

Figure E.1. Top view of bow-tie test structure depicting the measurement to be made.

To obtain the following measurements, consult ASTM standard test method E2244 entitled "Standard Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer."

---

filename of 3-D data set (optional) = [ ]
filename of 2-D data trace (optional) = [ ]
material = Poly1 ● Poly2 ○ stacked Poly1 and Poly2 ○
SiC-2 ○ SiC-3 ○
design dimension for D = [ ] μm
which bow-tie ? First ○ Second ● Third ○
magnification = [ ] ×
x-calibration factor (for the given magnification) = *calx* = [ ]
alignment ensured ? Yes ○ No ●

Input Sample Data   Reset this form

INPUTS (uncalibrated values):

$x1_{max}$ (i.e., $x1_{upper}$) = [ ] μm
$x1_{min}$ (i.e., $x1_{lower}$) = [ ] μm ($x1_{min} > x1_{max}$)
$x2_{min}$ (i.e., $x2_{lower}$) = [ ] μm ($x2_{min} > x1_{min}$)
$x2_{max}$ (i.e., $x2_{upper}$) = [ ] μm ($x2_{max} > x2_{min}$)

Calculate and Verify | Clear Outputs

OUTPUTS (calibrated values):

$D_{min} = (x2_{min} - x1_{min}) * calx =$ ______ μm

$D_{max} = (x2_{max} - x1_{max}) * calx =$ ______ μm

$D = (D_{min} + D_{max}) / 2 =$ ______ μm

$u_c = (D_{max} - D_{min}) / 6 =$ ______ μm

Make any necessary changes before submitting this form.

1. ☐ Please fill out the entire form.
2. ☐ The design dimension for D should be 38.5 μm.
3. ☐ The measured value for D is more than 5 μm from the design dimension.
4. ☐ Is the magnification appropriate given the design dimension for D ?
5. ☐ The x-calibration factor is "1." Has your data been calibrated ?
6. ☐ Alignment has not been ensured.
7. ☐ $x1_{min}$ should be greater than $x1_{max}$.
8. ☐ $x2_{min}$ should be greater than $x1_{min}$.
9. ☐ $x2_{max}$ should be greater than $x2_{min}$.
10. ☐ The calibrated values for $x1_{min}$ and $x1_{max}$ are greater than 10 μm apart.
11. ☐ The calibrated values for $x2_{min}$ and $x2_{max}$ are greater than 10 μm apart.

Please enter your email address: ______

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APPENDIX F – Data Analysis Sheet F

Data analysis sheet for in-plane deflection measurements from released part to fixed location

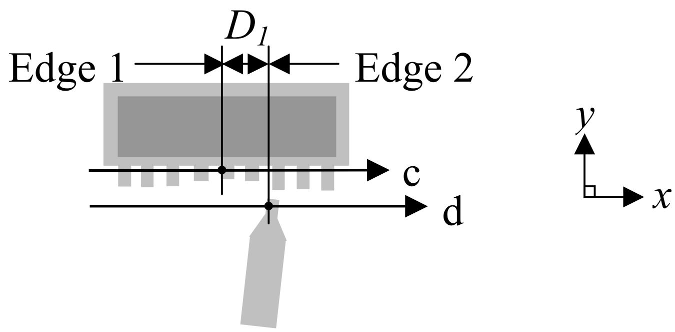

Figure F.1. Top view of a portion of the pointer test structure depicting the measurement to be made.

To obtain the following measurements, consult ASTM standard test method E2244 entitled "Standard Test Method for In-Plane Length Measurements of Thin, Reflecting Films Using an Optical Interferometer."

---

filename of 3-D data set (optional) = [ ]
filename of 2-D data traces (optional) = [ ]
[ ]
material = Poly1 ● Poly2 ○ stacked Poly1 and Poly2 ○
SiC-2 ○ SiC-3 ○
design displacement = [ ] μm
magnification = [ ] ×
x-calibration factor (for the given magnification) = *calx* = [ ]
alignment ensured ? Yes ○ No ●

Input Sample Data | Reset this form

INPUTS (uncalibrated values):

$x1_{max}$ (i.e., $x1_{lower}$) = [ ] μm
$x1_{min}$ (i.e., $x1_{upper}$) = [ ] μm ($x1_{min} > x1_{max}$)
$x2_{min}$ (i.e., $x2_{lower}$) = [ ] μm ($x2_{min} > x1_{min}$)
$x2_{max}$ (i.e., $x2_{upper}$) = [ ] μm ($x2_{max} > x2_{min}$)

sep (for the given magnification) = [ ] μm
Use 'lower' or 'upper' values for calculation ? Lower ● Upper ○

Calculate and Verify Clear Outputs

OUTPUTS (calibrated values):

$D_{1\text{-min}} = (x2_{\text{min}} - x1_{\text{min}}) * calx =$ ☐ µm

$D_{1\text{-max}} = (x2_{\text{max}} - x1_{\text{max}}) * calx =$ ☐ µm

$D_1 = (D_{1\text{-min}} + D_{1\text{-max}}) / 2 =$ ☐ µm

$u_c = (D_{1\text{-max}} - D_{1\text{-min}}) / 6 =$ ☐ µm

D_1 (using lower values) = $(x2_{\text{lower}} - x1_{\text{lower}}) * calx =$ ☐ µm

D_1 (using upper values) = $(x2_{\text{upper}} - x1_{\text{upper}}) * calx =$ ☐ µm

$u_c = (2 * sep * calx) / 3 =$ ☐ µm

Make any necessary changes before submitting this form.

1. ☐ Please fill out the entire form.
2. ☐ The designed displacement should be 0.0 µm.
3. ☐ The measured value for D_1 is 10 µm greater than the designed displacement.
4. ☐ Is the magnification appropriate given the value for D_1 ?
5. ☐ The *x*-calibration factor is "1." Has your data been calibrated ?
6. ☐ Alignment has not been ensured.
7. ☐ $x1_{\text{min}}$ should be greater than $x1_{\text{max}}$.
8. ☐ $x2_{\text{min}}$ should be greater than $x1_{\text{min}}$.
9. ☐ $x2_{\text{max}}$ should be greater than $x2_{\text{min}}$.
10. ☐ The calibrated values for $x1_{\text{min}}$ and $x1_{\text{max}}$ are greater than 10 µm apart.
11. ☐ The calibrated values for $x2_{\text{min}}$ and $x2_{\text{max}}$ are greater than 10 µm apart.
12. ☐ *sep* is greater than 2 µm or less than or equal to 0 µm. Is this correct ?

Please enter your email address: ☐

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(The 'submit' operation may take a minute.)

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APPENDIX G – Data Analysis Sheet G
Data analysis sheet for residual strain measurements

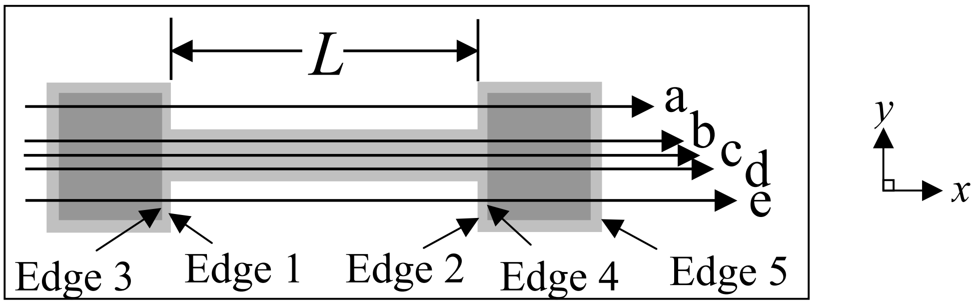

Figure G.1. Top view of fixed-fixed beam used to measure residual strain.

To obtain the following measurements, consult ASTM standard test method E2245 entitled "Standard Test Method for Residual Strain Measurements of Thin, Reflecting Films Using an Optical Interferometer."

---

filename of 3-D data set (optional) = [ ]
filename of 2-D data traces (optional) = [ ] [ ] [ ] [ ] [ ]
material = Poly1 ● Poly2 ○ stacked Poly1 and Poly2 ○
SiC-2 ○ SiC-3 ○ (therefore, t = [ ] µm)
design length = [ ] µm
which fixed-fixed beam ? First ○ Second ● Third ○
magnification = [ ] ×
x-calibration factor (for the given magnification) = $calx$ = [ ]
z-calibration factor (for the given magnification) = $calz$ = [ ]
alignment ensured ? Yes ○ No ●
Is this fixed-fixed beam exhibiting stiction ? Yes ○ No ●
If it is exhibiting stiction, do not fill out the remainder of this form.

Input Sample Data   Reset this form

INPUTS (uncalibrated values from Trace "a" or "e"):

$x1_{max}$ (i.e., $x1_{upper}$) = [ ] µm
$x1_{min}$ (i.e., $x1_{lower}$) = [ ] µm ($x1_{min} > x1_{max}$)
$x2_{min}$ (i.e., $x2_{lower}$) = [ ] µm ($x2_{min} > x1_{min}$)
$x2_{max}$ (i.e., $x2_{upper}$) = [ ] µm ($x2_{max} > x2_{min}$)

INPUTS (uncalibrated values from Trace "b"):

x_{1F} =		µm	z_{1F} =		µm	($x1_{ave} \leq x_{1F}$ * $calx$)
x_{2F} =		µm	z_{2F} =		µm	(inflection point)
x_{3F} =		µm	z_{3F} =		µm	(most deflected point)
						($x_{1F} < x_{2F} < x_{3F}$)
x_{1S} =		µm	z_{1S} =		µm	(same as x_{3F} and z_{3F})
x_{2S} =		µm	z_{2S} =		µm	(inflection point)
x_{3S} =		µm	z_{3S} =		µm	(x_{3S} * $calx \leq x2_{ave}$)
						($x_{1S} < x_{2S} < x_{3S}$)

INPUTS (uncalibrated values from Trace "c"):

x_{1F} =		µm	z_{1F} =		µm	($x1_{ave} \leq x_{1F}$ * $calx$)
x_{2F} =		µm	z_{2F} =		µm	(inflection point)
x_{3F} =		µm	z_{3F} =		µm	(most deflected point)
						($x_{1F} < x_{2F} < x_{3F}$)
x_{1S} =		µm	z_{1S} =		µm	(same as x_{3F} and z_{3F})
x_{2S} =		µm	z_{2S} =		µm	(inflection point)
x_{3S} =		µm	z_{3S} =		µm	(x_{3S} * $calx \leq x2_{ave}$)
						($x_{1S} < x_{2S} < x_{3S}$)

INPUTS (uncalibrated values from Trace "d"):

x_{1F} =		µm	z_{1F} =		µm	($x1_{ave} \leq x_{1F}$ * $calx$)
x_{2F} =		µm	z_{2F} =		µm	(inflection point)
x_{3F} =		µm	z_{3F} =		µm	(most deflected point)
						($x_{1F} < x_{2F} < x_{3F}$)
x_{1S} =		µm	z_{1S} =		µm	(same as x_{3F} and z_{3F})
x_{2S} =		µm	z_{2S} =		µm	(inflection point)
x_{3S} =		µm	z_{3S} =		µm	(x_{3S} * $calx \leq x2_{ave}$)
						($x_{1S} < x_{2S} < x_{3S}$)

Calculate and Verify   Clear Outputs

OUTPUTS (calibrated values):

$x1_{ave}$ =		µm	$x2_{ave}$ =		µm
L =		µm	u_L =		µm
s =			fromTrace "c"		

s = 1 (for downward bending fixed-fixed beams)
s = –1 (for upward bending fixed-fixed beams)

A_F =		µm	from Trace "b"
w_{1F} =			from Trace "b"
A_S =		µm	from Trace "b"
w_{3S} =			from Trace "b"

x_{eF} = [ ] μm from Trace "b"
x_{eS} = [ ] μm from Trace "b"
ε_{r0} = [ ] $\times 10^{-6}$ from Trace "b"
ε_r = [ ] $\times 10^{-6}$ from Trace "b"

A_F = [ ] μm from Trace "c"
w_{1F} = [ ] from Trace "c"
A_S = [ ] μm from Trace "c"
w_{3S} = [ ] from Trace "c"
x_{eF} = [ ] μm from Trace "c"
x_{eS} = [ ] μm from Trace "c"
ε_{r0} = [ ] $\times 10^{-6}$ from Trace "c"
ε_r = [ ] $\times 10^{-6}$ from Trace "c"
u_c = [ ] $\times 10^{-6}$ from Traces "b," "c," and "d"

A_F = [ ] μm from Trace "d"
w_{1F} = [ ] from Trace "d"
A_S = [ ] μm from Trace "d"
w_{3S} = [ ] from Trace "d"
x_{eF} = [ ] μm from Trace "d"
x_{eS} = [ ] μm from Trace "d"
ε_{r0} = [ ] $\times 10^{-6}$ from Trace "d"
ε_r = [ ] $\times 10^{-6}$ from Trace "d"

Make any necessary changes before submitting this form.

1. [ ] Please fill out the entire form.
2. [ ] The thickness value is different than what the fabricator specified.
3. [ ] The design length should be 400, 450, 500, 550, 600, 650, 700, 750, or 800 μm.
4. [ ] The measured value for L is more than 5 μm from the design length.
5. [ ] Is the magnification appropriate given the design length ?
6. [ ] The x-calibration factor is "1." Has your data been calibrated ?
7. [ ] The z-calibration factor is "1." Has your data been calibrated ?
8. [ ] Alignment has not been ensured.
9. [ ] $x1_{\text{min}}$ should be greater than $x1_{\text{max}}$.
10. [ ] $x2_{\text{min}}$ should be greater than $x1_{\text{min}}$.
11. [ ] $x2_{\text{max}}$ should be greater than $x2_{\text{min}}$.
12. [ ] The calibrated values for $x1_{\text{min}}$ and $x1_{\text{max}}$ are greater than 10 μm apart.
13. [ ] The calibrated values for $x2_{\text{min}}$ and $x2_{\text{max}}$ are greater than 10 μm apart.
14. [ ] In Traces "b," "c," and "d," the value for s is not the same.
15. [ ] (x_{3F}, z_{3F}) should be the same as (x_{1S}, z_{1S}) in all traces.
16. [ ] $x1_{\text{ave}}$ should be $\leq (x_{1F} * calx)$ in all traces.
17. [ ] $(x_{3S} * calx)$ should be $\leq x2_{\text{ave}}$ in all traces.
18. [ ] In all traces, make sure $(x_{1F} < x_{2F} < x_{3F})$.
19. [ ] In all traces, make sure $(x_{1S} < x_{2S} < x_{3S})$.
20. [ ] For Trace "b," $|[(x_{2F} * calx) - x_{eF}]|$ = [ ] μm. This should be < 5 μm.

21. ☐ For Trace "b," $\left|[(x_{2S} * calx) - x_{eS}]\right|$ = ☐ µm. This should be < 5 µm.
22. ☐ For Trace "c," $\left|[(x_{2F} * calx) - x_{eF}]\right|$ = ☐ µm. This should be < 5 µm.
23. ☐ For Trace "c," $\left|[(x_{2S} * calx) - x_{eS}]\right|$ = ☐ µm. This should be < 5 µm.
24. ☐ For Trace "d," $\left|[(x_{2F} * calx) - x_{eF}]\right|$ = ☐ µm. This should be < 5 µm.
25. ☐ For Trace "d," $\left|[(x_{2S} * calx) - x_{eS}]\right|$ = ☐ µm. This should be < 5 µm.

Please enter your email address: ☐

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APPENDIX H – Data Analysis Sheet H

Data analysis sheet for strain gradient measurements

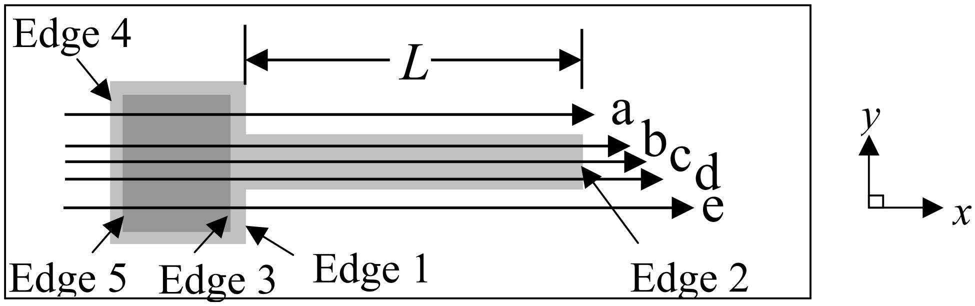

Figure H.1. Top view of cantilever test structure used to measure strain gradient.

To obtain the following measurements, consult ASTM standard test method E2246 entitled “Standard Test Method for Strain Gradient Measurements of Thin, Reflecting Films Using an Optical Interferometer.”

---

filename of 3-D data set (optional) = [ ]

filename of 2-D data traces (optional) = [ ]

[ ] [ ]

[ ] [ ]

material = Poly1 ● Poly2 ○ stacked Poly1 and Poly2 ○

SiC-2 ○ SiC-3 ○

design length = [ ] μm

which cantilever ? First ○ Second ● Third ○

magnification = [ ] ×

x-calibration factor (for the given magnification) = *calx* = [ ]

z-calibration factor (for the given magnification) = *calz* = [ ]

alignment ensured ? Yes ○ No ●

Is this cantilever exhibiting stiction ? Yes ○ No ●

If it is exhibiting stiction, do not fill out the remainder of this form.

Input Sample Data   Reset this form

INPUTS (uncalibrated values from Trace “a” or “e”):

$x1_{max}$ (i.e., $x1_{upper}$) = [ ] μm

$x1_{min}$ (i.e., $x1_{lower}$) = [ ] μm ($x1_{min} > x1_{max}$)

INPUTS (uncalibrated values from Trace “b”):

x_1 = [ ] μm z_1 = [ ] μm ($x1_{ave} \leq x_1 * calx$)

x_2 = [ ] μm z_2 = [ ] μm ($x1_{ave} \leq x_2 * calx$)

x_3 = [ ] μm z_3 = [ ] μm ($x1_{ave} \leq x_3 * calx$)

INPUTS (uncalibrated values from Trace "c"):

x_1 = [ ] μm z_1 = [ ] μm ($x1_{ave} \leq x_1 * calx$)
x_2 = [ ] μm z_2 = [ ] μm ($x1_{ave} \leq x_2 * calx$)
x_3 = [ ] μm z_3 = [ ] μm ($x1_{ave} \leq x_3 * calx$)

INPUTS (uncalibrated values from Trace "d"):

x_1 = [ ] μm z_1 = [ ] μm ($x1_{ave} \leq x_1 * calx$)
x_2 = [ ] μm z_2 = [ ] μm ($x1_{ave} \leq x_2 * calx$)
x_3 = [ ] μm z_3 = [ ] μm ($x1_{ave} \leq x_3 * calx$)

[Calculate and Verify] [Clear Outputs]

OUTPUTS (calibrated values):

$x1_{ave}$ = [ ] μm
s = [ ] fromTrace "c"
s = 1 (for downward bending cantilevers)
s = −1 (for upward bending cantilevers)

R_{int} = [ ] μm from Trace "b"
a = [ ] μm from Trace "b"
b = [ ] μm from Trace "b"
s_g = [ ] m^{-1} from Trace "b"

R_{int} = [ ] μm from Trace "c"
a = [ ] μm from Trace "c"
b = [ ] μm from Trace "c"
s_g = [ ] m^{-1} from Trace "c"
u_c = [ ] m^{-1} from Traces "b," "c," and "d"

R_{int} = [ ] μm from Trace "d"
a = [ ] μm from Trace "d"
b = [ ] μm from Trace "d"
s_g = [ ] m^{-1} from Trace "d"

Make any necessary changes before submitting this form.

1. [ ] Please fill out the entire form.
2. [ ] The design length should be 400, 450, 500, 550, 600, 650, 700, 750, or 800 μm.
3. [ ] Is the magnification appropriate given the design length ?
4. [ ] The x-calibration factor is "1." Has your data been calibrated ?
5. [ ] The z-calibration factor is "1." Has your data been calibrated ?
6. [ ] Alignment has not been ensured.
7. [ ] $x1_{min}$ should be greater than $x1_{max}$.
8. [ ] The calibrated values for $x1_{min}$ and $x1_{max}$ are greater than 10 μm apart.
9. [ ] In Trace "b," the calibrated values of x_1, x_2, and x_3 should be $\geq x1_{ave}$.

10. ☐ In Trace "c," the calibrated values of x_1, x_2, and x_3 should be $\geq x1_{\text{ave}}$.
11. ☐ In Trace "d," the calibrated values of x_1, x_2, and x_3 should be $\geq x1_{\text{ave}}$.
12. ☐ In Traces "b," "c," and "d," the value for s is not the same.

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